

Global Network of Optical Magnetometers for Exotic Physics

Novel scheme for exotic physics searches

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We present a novel experimental scheme enabling investigation of transient exotic spin couplings. The scheme is based on synchronous measurements of optical-magnetometer signals of several devices operating in magnetically shielded environments in distant locations ($\gtrsim 100$ km). Although signatures of such exotic couplings may be present in a signal of the single magnetometer, it would be challenging to extract them from noise. With correlation measurements of signals from the magnetometers, not only the effects can be identified but their nature may also be investigated. The ability of the network to investigate physics beyond the Standard Model is discussed by considering the spin coupling to stable topological defects (e.g. domain walls) of axion-like fields. It is shown that the network consisting of sensitive optical magnetometers is capable to probe an axion-like-field parameter space unconstrained by other experiments.

I. INTRODUCTION

Among all magnetometric techniques, optical magnetometry [1, 2] presently offers the possibility of the most sensitive magnetic-field measurements [3]. Intrinsic sensitivity of optical magnetometers (OMAGs) to spin dynamics does not limit their application to magnetic-field detection but also enables investigation of other spin interactions, including non-electromagnetic ones (see Ref. [2] and references therein). In particular, OMAGs can be applied to probe couplings between spins and hypothetical fields not predicted by the Standard Model. Such exotic fields are postulated by a variety of theories [4–13]. One manner in which they could manifest themselves on Earth is as transient events. A particular example would be transient coupling of spins to certain constituents of dark matter (DM) and dark energy (DE) [12].

Most experimental DM searches aim at direct detection of some variety of particles that feebly interact with

ordinary baryonic matter, e.g., Weakly Interacting Massive Particles (WIMPs) or axions [14]. Until now, however, all the searches have produced only upper limits on the interaction strength between DM and ordinary baryonic matter. Over the years, however, alternative candidates for DM have been proposed. For example, if DM consists of light axions or axion-like particles, it behaves more like a coherent field than a collection of uncorrelated particles [15, 16]. In some theoretical scenarios, because the vacuum energy of the axion field is non-zero, the field oscillates at a specific frequency and hence it would not produce static effects on baryonic matter. Such DM scenarios also tend to be generated by stable topological defects [12, 17–23], e.g., an axion-like field with a domain structure [12]. When the Earth crosses one of the domain walls (DWs) separating regions with different vacuum expectation values of the axion-like field, a torque can be exerted on leptonic or baryonic spins. Such a DW-crossing event could lead to transient signal detectable with modern state-of-the-art OMAGs [12]. Based on astronomical constraints, however, one can show that wall-crossing events are rare and brief [12], so the major issue becomes separation of the transient signals induced by the DW crossing from transient signals generated by environmental and technical noise. Reliable rejection of OMAG's transient signals due to other effects requires development of a new approach.

In this paper, we demonstrate the principles of a new

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technique for detecting transient signals of exotic origin using a global network of synchronized OMAGs (the Global Network of Optical Magnetometers for Exotic physics, GNOME). Although the network may be used for detection of a variety of transient interactions heralding physics beyond the Standard Model, here, for concreteness, we focus our considerations on the transient effects induced by crossing through the DWs of axion-like field. We demonstrate that application of the GNOME enables probing presently unconstrained parameters of the field.

The article is organized as follows. First, a general discussion of OMAGs with a special attention drawn to their most important characteristics relevant for detection of exotic transient events is provided. Next, we review the theory of domain walls of axion-like fields relevant to their detection by the GNOME (Sec. III). Section IV discusses a first demonstration experiment using synchronously detected signals of two OMAGs separated by about 9000 km. These two magnetometers form the first elements of the envisioned future GNOME. The principles that form the basis of the GNOME data analysis are outlined in Sec. V. Finally, the prospects of the GNOME are discussed in Sec. VI and conclusions are drawn in Sec. VII.

II. CHARACTERISTICS OF OMAGS RELEVANT FOR THE DETECTION OF TRANSIENT EFFECTS

Detection of transient events that weakly perturb atomic spins requires OMAGs with specific characteristics. In particular, a suitable device needs to have high enough sensitivity to detect small changes in spin dynamics. Moreover, its response to abrupt changes of spin behavior needs to be suitably fast not to distort or average out the signals, so that their time-domain signature can be reliably understood and compared between different GNOME sites. High sensitivity and high bandwidth, however, may not always be compatible with each other. Typically, high-sensitivity OMAGs also have characteristically slow spin relaxation times, which typically leads to narrower bandwidths, whereas high bandwidth devices typically have faster spin relaxation times, which degrades sensitivity. Below, we discuss fundamental and technical limitations of OMAG sensitivity as well as factors determining the bandwidth of the devices. Discussion of other characteristics of the magnetometers, relevant for detection of transient signals, is also provided.

In OMAGs, detection of magnetic fields occurs in a three-phase process. First, atoms are optically pumped; next, they evolve under the influence of external fields; finally, their quantum state is detected with light [63]. While this scheme allows for the most sensitive measurements of magnetic fields, it also sets a fundamental limit on the sensitivity of OMAGs. The limit results from the quantum nature of photons and atoms and the coupling

between them. In the most general form, the fundamental limit of the sensitivity $\delta B_f = \sqrt{\delta B_{at}^2 + \delta B_{ph}^2 + \delta B_{ba}^2}$, where δB_{at} is the magnetic-sensitivity limit due to spin-projection noise (SPN), δB_{ph} is the limit related to photon shot noise, and δB_{ba} is the limit associated with back-action of the probe light on the atoms. The projection noise originates from the Heisenberg uncertainty principle $\delta F_i^2 \delta F_j^2 \geq |\langle [F_i, F_j] \rangle|^2 / 4 = \hbar^2 \langle F_k \rangle^2 / 4$, where $F_{i,j,k}$ are three components of the spin \mathbf{F} and $[\cdot]$ denotes the commutator. When this relation becomes an equality, the SPN-limited magnetic-field sensitivity δB_{at} may be written as [2]

$$\delta B_{at} = \frac{1}{g\mu_B} \sqrt{\frac{1}{N_{at}T_2\tau}}, \quad (1)$$

where N_{at} is the total number of atoms involved in the light-atom interaction, T_2 is the transverse spin-relaxation time, τ is the duration of the measurement, g is the Landé factor, μ_B is the Bohr magneton, and we use natural units ($\hbar = c = 1$) [64]. Equation (1) reveals two strategies to improve the sensitivity of OMAGs. The first consists in prolonging the transverse spin-relaxation time T_2 , for example, by containing the atoms in a glass cell with antirelaxation coating that preserves spin polarization upon atomic collisions with cell walls or introducing a buffer gas with a low spin-depolarization cross-section into the cell to limit diffusion to the walls. The second approach relies on increasing the number of atoms N_{at} . Both approaches are used in OMAGs and in fact, herein we discuss experimental results obtained with OMAGs exploiting both methods (Sec. V).

The second contribution δB_{ph} to the fundamental magnetometric sensitivity δB_f is associated with the fluctuation of the number of photons in the light beam used for probing the spins. Due to Poissonian statistics of photons, the intensity and polarization-state of light can only be determined with a finite precision $\propto (\dot{N}_{ph}\tau)^{-1/2}$, where \dot{N}_{ph} is a number of photons of the probe beam hitting detector per unit time. This sets a limit on the precision with which the spin state can be determined and hence the limit on the magnetometric sensitivity. It is important to note, however, that this contribution can be reduced by detuning the probe light frequency away from a resonant optical transition and simultaneously increasing the light intensity. The photon shot-noise limited sensitivity improves due to the increase in \dot{N}_{ph} , and the probe light only weakly affects the medium while the state can still be efficiently determined (absorption on an isolated transition scales as $1/\Delta^2$ and dispersion as $1/\Delta$, where Δ is detuning). Hence, the contribution of the photon shot noise to the total magnetometric sensitivity δB_f may be reduced so that $\delta B_{ph} \ll \delta B_{at}$.

The last source of fundamental noise comes from the Stark shift of energy levels induced by quantum fluctuations of light intensity and polarization (back action) [26]; fluctuations of energies of magnetic sublevels introduce uncertainty in spin precession and hence limit mag-

netometric sensitivity. Yet, there are means of reducing or eliminating backaction [24, 27, 28]. One approach is based on the same principle as used to reduce δB_{ph} , i.e., detuning the probe-light frequency far from any resonant transition [29]. This approach allows reduction of δB_{ba} so that, under optimized conditions, Eq. (1) accurately represents the fundamental sensitivity limit of the magnetic-field measurements with OMAGs ($\delta B_f \approx \delta B_{at}$).

Typically, on top of fundamental noise, there is technical noise δB_t . For example, optical noise may be induced by mechanical vibration of optical elements or air turbulence in the probe-beam optical path. Electronics used in light detection can also contribute to technical noise. With appropriate experimental measures, the influence of the noise on overall magnetometric sensitivity may be reduced but it cannot be completely eliminated. Thus, in many cases, it is a significant (sometimes dominant) contribution to OMAG sensitivity.

A different source of noise originates from uncontrollable magnetic fields. Such fields result in random response of OMAGs thus reduces the sensitivity of an OMAG to non-magnetic interactions affecting the atomic spins. In the case of OMAGs enclosed inside a magnetic shield, a common configuration for precision measurements, uncertainty in spin-dynamics measurements may be introduced by external magnetic fields penetrating into the shield [65], thermal currents induced in the shield material, and instability of the current source used for generating magnetic fields. The noise may be reduced by application of active cancellation of the field outside the shield and/or used of low electric conductivity high magnetic susceptibility shielding materials [66]. Another common approach is to employ comagnetometry techniques, where the magnetic field is measured by multiple species expected to have different couplings to the exotic fields, allowing subtraction or cancellation of magnetic field noise.

Although OMAGs do not have intrinsic $1/f$ noise, existence of technical noise suggests an advantage of detection of optical signals at frequencies higher than $1/f$ -“knee”. This may be achieved either by modulation of the probe light, i.e., by application of intensity, frequency, or polarization modulation, and phase-sensitive detection of the signal, or by operation of the devices in non-zero magnetic fields $B \gg \hbar/T_2 g\mu_B$. In the latter case, the output signal of the magnetometer is modulated at the Larmor frequency $\omega_L = g\mu_B B/\hbar$ or a multiple thereof, which enables filtering of the low-frequency noise. To detect such higher-frequency signals, however, OMAGs with broad dynamic ranges are required.

Operation at non-zero magnetic fields raises another important issue in magnetic-field detection. Optical magnetometers enable either scalar measurements, where the device response depends on the magnitude of a magnetic field, or vector measurements, where it is determined by specific vector components of the field. However, even scalar magnetometers operating at non-zero magnetic fields become primarily sensitive to the field changes

along the dominant component of the field; transverse components of the field add as second-order corrections to the total-field magnitude B . Moreover, modulation of the magnetic field in three spatial directions enables a scalar magnetometer to detect the three vector components of the field [30]. There also exist techniques enabling conversion of a scalar magnetometer into a vector magnetometer without the necessity of applying a modulated magnetic field [31]. The ability to determine not only a magnitude but also the direction of the spin-coupling field may have implications for the envisioned detection of transient effects due to exotic interactions.

Another characteristic of OMAGs, particularly important in detection of transient signals, is bandwidth. For typical OMAGs (see Ref. [2] and references therein), the response of the magnetometer to small field changes is equivalent to a response of a first-order low-pass filter with the time constant T_2 [32]. Hence the natural bandwidth of such OMAGs is given by $(2\pi T_2)^{-1}$, which for shorter measurement times, i.e., $\tau < T_2$, takes the form $(2\pi\tau)^{-1}$. OMAG bandwidth can be broadened by shortening T_2 , which can be, for example, accomplished by increasing intensity of the probe light (power broadening). That increase of the magnetometer bandwidth often occurs at the cost of its sensitivity [Eq. (1)]. Therefore, optimized operation of OMAGs requires a compromise between the two quantities. It should be noted, however, that application of quantum nondemolition measurements enables to achieve sensitive magnetic-field measurements at high bandwidth [33, 34].

In order to detect transient spin couplings, the signal characteristics must fall into the detection capabilities of the OMAGs used. Table I summarizes characteristics of various OMAGs with potential applicability to the GNOME. Although they differ in various aspects, many of them have the potential to be successfully employed as GNOME sensors.

III. THEORETICAL BACKGROUND

A specific example of exotic spin coupling that may be detectable with the GNOME is the transit of the Earth through a domain wall (DW) of a light pseudoscalar (axion-like) field [12]. Stable domain structure of axion-like fields is a consequence of certain Standard Model extensions [45–48]. Domains form out of the initially random distribution of the vacuum expectation values of the axion-like field as the Universe expands and cools. In this scenario, DWs separate regions of space with different energy vacua [49]. Importantly, based on astrophysical constraints, only light axion-like fields can build DWs that persist to the present epoch [67].

A detailed theoretical background of the optical detection of wall crossings is presented elsewhere [12]. Here we only briefly review the concept. We start with considering a hypothetical pseudoscalar field $a(\mathbf{r})$ that permeates the Universe and forms a domain structure. As

TABLE I: Various OMAGs characteristics important for detecting transient signals due to exotic spin couplings. δE_f and δE_d are the fundamental and demonstrated OMAG sensitivities in energy units. The names of the magnetometers indicate the type of the device. HFP is an abbreviation of hexafluorobenzene.

Name	Element(s)/ Compound(s)	δE_f (eV/ $\sqrt{\text{Hz}}$)	δE (eV/ $\sqrt{\text{Hz}}$)	T_2 (ms)	Spin coupling	Ref.
SERF	K+N ₂ + ⁴ He	2.9×10^{-22}	3.1×10^{-21}	100	Total	[3]
μ -SERF	Cs	3.9×10^{-20}	5.8×10^{-20}	5	Total	[35]
NMR-SERF hybrid	pentane-HFB	10^{-23}	3.5×10^{-19}	20000	Nuclear	[36]
NMOR	Rb	5.8×10^{-21}	5.8×10^{-19}	300	Total	[37]
FM/AM NMOR	Rb	4×10^{-20}	1.2×10^{-18}	300	Total	[38–40]
M _x	K, Cs	1.4×10^{-19}	5.8×10^{-19}	300	Total	[41, 42]
μ -M _x	Cs	7.2×10^{-19}	1.4×10^{-18}	0.06	Total	[43]
Hg EDM	Hg	2×10^{-24}	2.5×10^{-22}	100000	Nuclear	[44]

shown in [12], a specific realization of the field existing between neighboring domains with different energy-degenerate vacua (with the DW centered at $z=0$)

$$a(z) = 4a_0 \arctan[\exp(m_a z)], \quad (2)$$

where a_0 is the characteristic amplitude of the field and m_a is the pseudoscalar-particle mass. Coupling between the axion-like-field gradient ∇a and the spin \mathbf{F} arising during the domain-wall crossing is described by the Hamiltonian [68]

$$H_{\text{DW}} = \frac{\mathbf{F} \cdot \nabla a}{F f_{\text{ef}}}, \quad (3)$$

where f_{ef} is the effective decay constant in units of energy. f_{ef} depends on the atomic structure of the particles used in a specific OMAG and is a combination of electron f_e , proton f_p , and nucleon decay constants f_n . By substituting Eq. (2) into Eq. (3), the Hamiltonian H_{DW} can be expressed using the field parameters m_a and a_0

$$H_{\text{DW}} = \frac{2}{f_{\text{ef}}} \frac{a_0 m_a \cos \varphi}{\cosh(m_a z)}, \quad (4)$$

where φ is the angle between the spin \mathbf{F} and the field gradient ∇a .

Until now, only lower bounds on the electron f_e , neutron f_n , and electron f_p proton decay constants have been established by astronomical observations ($|f_{e,n,p}| > 10^9$ GeV). Below we show that the coupling can be further investigated using the GNOME.

The thickness of the DW d is determined by the pseudoscalar-particle mass m_a via

$$d = \frac{2}{m_a}. \quad (5)$$

Consequently, the mass also limits the duration of the transient signal $\Delta t = d/v_\perp$, where v_\perp is the relative speed between the DW and the OMAG. At distances much larger than d , the walls may be characterized by the tension σ , which is the mass/energy per unit area of

the DW. In the considered case, it can be written as a function of the field parameters

$$\sigma \approx m_a a_0^2. \quad (6)$$

The tension can be related to the DW energy density ρ_{DW} via $\rho_{\text{DW}} \approx \sigma/L$, where L is the characteristic size of the domain. Importantly, the density ρ_{DW} needs to be smaller than the DM density ρ_{DM} ($\rho_{\text{DM}} \approx 0.4$ GeV/cm³) or the DE energy density ρ_{DE} ($\rho_{\text{DE}} \approx 0.4 \times 10^{-5}$ GeV/cm³). Determination of the tension also requires knowledge about the characteristic size of the domain L . Since it is not possible to determine L without further assumptions about the specific mechanism of domain-structure formation, here we treat L as a free parameter and constrain it from an experimental perspective, i.e., the experimental feasibility implies that the average time T between two wall crossings should not be longer than 10 years. By taking into account the speed of the solar system relative to the Galactic frame ($v \approx 10^{-3}c$), a DW-crossing event will occur within a time-span of 10 years if the domain size is less than 10^{-2} ly.

Combining Eqs. (4) and (6), one obtains the formula for the effective decay constant f_{ef} at the center of the wall ($z = 0$)

$$f_{\text{ef}} = \frac{2\sqrt{\rho_{\text{DW}} L m_a}}{\delta E} \cos \varphi, \quad (7)$$

where δE is the sensitivity of an OMAG in energy units.

Figure 1 presents the parameter space that can be probed with OMAGs. The shaded region indicates the parameter range that can be realistically probed with the OMAG of a sensitivity of $\approx 3 \times 10^{-20}$ eV/ $\sqrt{\text{Hz}}$ and a characteristic DW-size of 10^{-2} ly. The plot indicates that detection of axion-like field domain structure with the DM energy density ρ_{DM} is possible with the envisioned GNOME. Moreover, with higher sensitivity magnetometers (see Table I), the parameter space can be further explored enabling probing DWs with the density ρ_{DW} , given by the DE density ρ_{DE} [12].

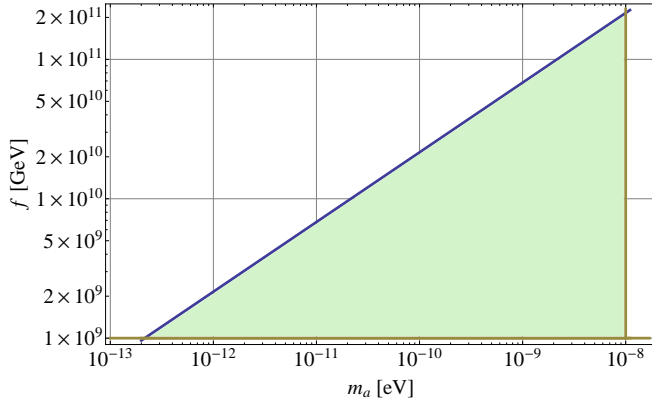


FIG. 1: Parameter space of the axion-like field with a domain structure that can be probed with the GNOME (green shaded region). The blue line limits the space due to the sensitivity of applied magnetometers (assumed here to be 2.9×10^{-20} eV/ $\sqrt{\text{Hz}}$, which corresponds to a sensitivity of 10^{-15} T/ $\sqrt{\text{Hz}}$ of the cesium NMOR magnetometer). The two green lines arise from exiting limits from the astronomical observations [50] (the horizontal line at 10^9 GeV) and the duration of the experiment being less than 10 years (vertical line at 10^{-8} eV). For the plot the DW energy density was assumed to equal the DM energy density ($\rho_{\text{DM}} \approx 0.4$ GeV/cm 3).

Being able to detect a single 10-ms duration event in a 10-year time-span requires continuous and robust operation of the magnetometer on a comparable time scale. Figure 2 presents the average time between DW crossings as a function of the decay constant f_{ef} an OMAG with a sensitivity equal to 2.9×10^{20} eV/ $\sqrt{\text{Hz}}$ (1 fT/ $\sqrt{\text{Hz}}$). The

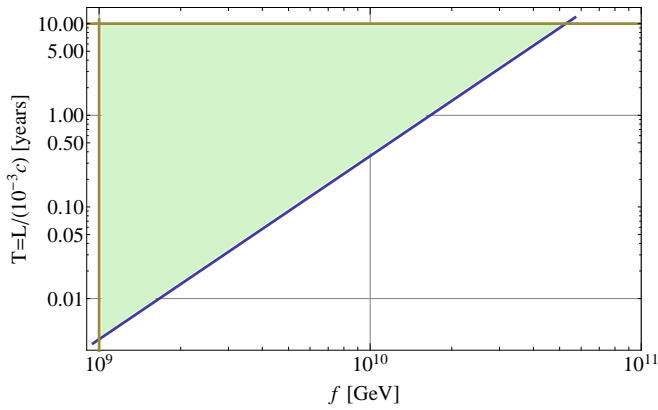


FIG. 2: Average time between successive DW crossings T as a function of the effective decay constant f_{ef} (green shaded). The blue line is determined by a magnetometer sensitivity of 2.9×10^{20} eV/ $\sqrt{\text{Hz}}$ corresponding to 10 T/ $\sqrt{\text{Hz}}$, while the meaning of green lines is the same as in Fig. 1.

results show that the GNOME can probe significant regions of parameter space in as few as three days of continuous operation. The accessible parameter space expands rapidly with increasing duration of the measurements.

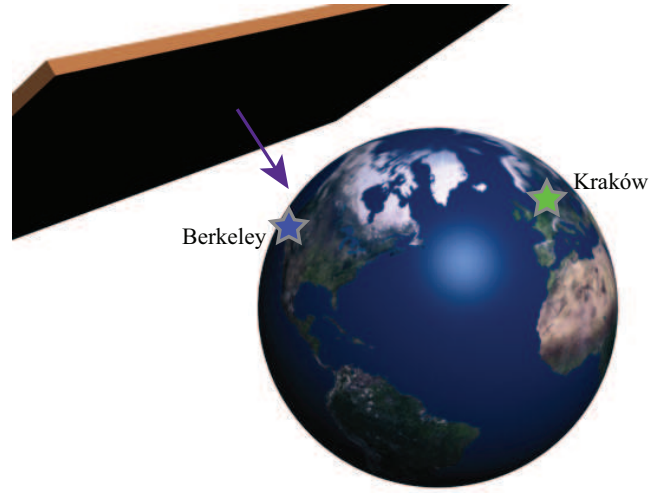


FIG. 3: The concept of the synchronized-magnetometer arrangement. OMAGs located at globally separated locations record signals with a time synchronization provided by the GPS. By synchronously detecting and correlating magnetometer signals, transient events of global character may be identified. In particular, correlating signals of at least four devices enables detection of spatiotemporal character of the event. Here, two devices located in Kraków and Berkeley are used to search for transient signals induced by crossing of a DW of an axion-like field.

In principle, the parameters of the model can be constrained with a single magnetometer. A particular problem for a search carried out with a single OMAG is the appearance of brief spikes in the OMAG signal related to technical noise or abrupt magnetic field changes. In a single device, rejection of these false-positive signals is difficult. At the same time, coincident measurements between two or more instruments are helpful in rejecting such signals; they provide consistency checks, since a signal would be expected to exist in all instruments whereas environmentally induced events are not typically correlated in the time window required for coincidence. Furthermore, information about a putative event such as its impinging direction can be determined by triangulation if several instruments (at least four) are taking data simultaneously (see discussion in Sec. VI). These features clearly show that synchronous operation of multiple synchronized, geographically separated OMAGs within the proposed global network may facilitate searches for such transient signals of astrophysical origin.

IV. EXPERIMENTAL APPARATUS

The concept of the experimental apparatus is shown in Fig. 3. Since detailed description of the two OMAGs used in our experiment may be found elsewhere [38, 51], we only briefly review the most important elements of

the devices. Both magnetometers use rubidium vapors as the magneto-optically active medium. In the Kraków magnetometer, the atomic vapor is contained in a paraffin-coated evacuated cylindrical glass cell with volume $\approx 3 \text{ cm}^3$. The vapor cell is maintained at about 50°C corresponding to an atomic density of roughly $10^{11} \text{ atoms/cm}^3$. The relaxation rate of the atomic ground state is $2\pi \times 30 \text{ s}^{-1}$, which yields a fundamental sensitivity δB_f of $\approx 3 \text{ fT}/\sqrt{\text{Hz}}$ (spin-projection limited) [69]. The second magnetometer (Berkeley) exploits a microfabricated vapor cell [52] of a volume of 0.01 cm^3 that is heated up to about 200°C . Operation in the spin-exchange relaxation free regime [53] allows eliminations of relaxation due to spin-exchange collisions, one of the main ground-state polarization-relaxation mechanisms. Application of the technique allows one to obtain a ground-state relaxation rate of about $2\pi \times 400 \text{ s}^{-1}$, which in combination with 3-4 orders of magnitude higher density yields a similar sensitivity as for the other setup, i.e., about $1 \text{ fT}/\sqrt{\text{Hz}}$ [70]. Both magnetometers thus have the capability to detect a DW crossing and probe the parameter space.

Both magnetometers are placed inside multilayer magnetic shields made of μ -metal with the innermost layer made of ferrite [71]. The shields reduce external magnetic fields by a factor 10^6 . Inside the shield atoms are subjected to a stable, well-controlled magnetic field generated by a set of three-dimensional magnetic-field coils. In the Kraków magnetometer a field with a magnitude of 10^{-7} T is applied, while at Berkeley the applied-field magnitude is $\approx 5 \times 10^{-8} \text{ T}$.

The outputs of the magnetometers are acquired using custom-made devices based on Trimble Resolution-T GPS (Global Positioning System) time receivers. The data acquisition devices provides time markers separated by one second with a precision of about 80 ns synchronized with a quartz clock built into the devices. The acquisition devices can record simultaneously signals in four channels with at a rate of 1000 samples/s. Each one-second-long record is stored on a memory card with a header containing information on time, location, etc. Every record is transmitted to the computer (via serial port) where it is binned into groups of 10-1000 records (typically 2-minute long bins are generated). The data are stored with computers located at the respective locations, and every 1-2 hours the information is exchanged between Krakow and Berkeley using File Transfer Protocol (FTP). In this manner, the complete set of data is accessible in either of the locations. The detailed discussion of the GPS-synchronized data-acquisition devices is presented in Ref. [54].

V. RESULTS AND DATA ANALYSIS

Figure 4 presents magnetometer signals measured synchronously in the two locations (Berkeley, California, USA and Kraków, Poland) over a period of about

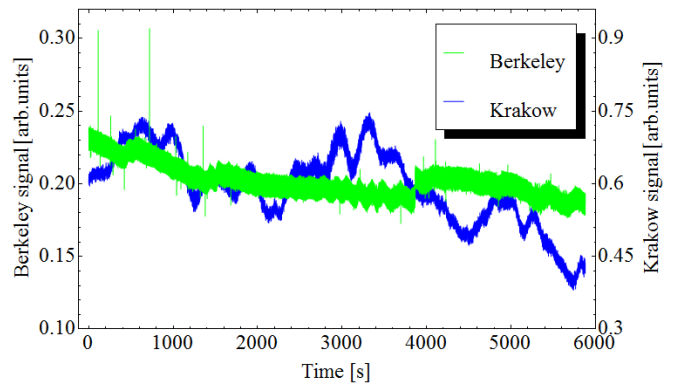


FIG. 4: Synchronously detected signals of the two OMAGs located in Kraków and Berkeley. The signal in the Kraków magnetometer was measured at a field of 100 nT, whereas the Berkeley magnetometer operated at 50 nT. The data acquisition rate was 256 samples per second.

1.5 hours. Relative to the mean amplitude of the signal, the long-term drift of the Kraków magnetometer is larger than that of the Berkeley magnetometer. This is most likely attributable to instability of the laser frequency, which will be addressed in the future by implementation of laser-stabilization techniques. The Berkeley magnetometer signal exhibits short duration ($\lesssim 4 \text{ ms}$) spikes of relatively large amplitudes not observed in the Kraków signal. Auxiliary tests verified that the noise spikes originated from electronic pick-up, a problem that will be addressed in the future.

In many respects, identification of a DW-crossing event using the GNOME is similar to searches for gravitational-wave bursts with a system of long-baseline laser interferometers [such as the Laser Interferometer Gravitational-Wave Observatory (LIGO), the Virgo detector, GEO 600, and TAMA 300] [55]. Both types of experiments aim to identify and characterize transient signals and search for time-domain correlations between the transient signals from different detectors. Importantly, the field of transient gravitational-wave astronomy has developed a variety of statistical methods to identify brief (duration $\lesssim 1 \text{ s}$) signals correlated among different detectors but otherwise generic in noisy time series data.

As a proof-of-principle demonstration, we have applied one of the methods upon which such statistical analysis is based, the “excess power” statistic [56], to the synchronous magnetometer data from the Kraków and Berkeley sites. The analysis is carried out as follows. First, an estimation of the power spectral density (PSD) over several continuous, overlapping segments of the data is made for the data from each individual detector. These spectra are updated at regular intervals and combined with previous measurements using a running median exponentially-weighted history (this is a filter that weights contributions to the moving average by a factor that decreases exponentially with the time

since the data was acquired). The PSD is then used to whiten the data, ideally, producing a stream of Gaussian distributed, zero-mean, unity variance random variables characterizing the data set. Whitening the data removes correlations between the different variables used to characterize the magnetometer signals. The stream of whitened data is then passed through a bank of band-limited filters producing several channels of filtered data. The filters are Hann windows in the frequency domain, which are themselves whitened with the PSD. The resulting streams are a discrete localization of the energy in the original data stream described by “tiles” having a time-frequency extent bounded by a bandwidth $\Delta\nu_f$ (the bandwidth of the filters) and duration δt . The resulting tile is constructed so as to have N_{DOF} independent degrees of freedom such that $N_{\text{DOF}} = 2\delta\nu_f\delta t$ [57].

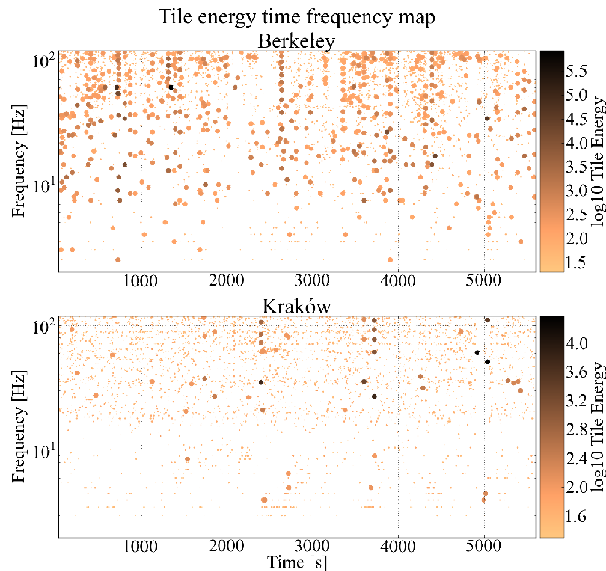


FIG. 5: Time-frequency maps of outlying tile energies of the Berkeley (top) and Krakow (bottom) OMAG data. Each dot represents a tile characterized by its power-weighted central time (x -axis), Fourier frequency (y -axis), and tile energy (color and dot size). The large markers indicate tiles with a normalized tile energy greater than 100. Large tile energies are likely caused by discontinuities (which cause short but broadband responses) in the data or environmental influences within the instruments themselves.

The final product is a time/frequency map of tiles describing the whitened signal energy (Fig. 5). Under the conditions of stationarity (the PSD does not fluctuate on the time scale of the estimation process) and Gaussianity (the data samples have a distribution matching the Gaussian distribution), the tile energies are distributed as a χ^2 distribution with degrees of freedom as described above. Thus the significance of any tile’s energy is well-understood and the statistical probability of outlier tiles can be measured. Correlated transient signals from different magnetometers can be searched for by using the time/frequency tile maps to find overlapping events with

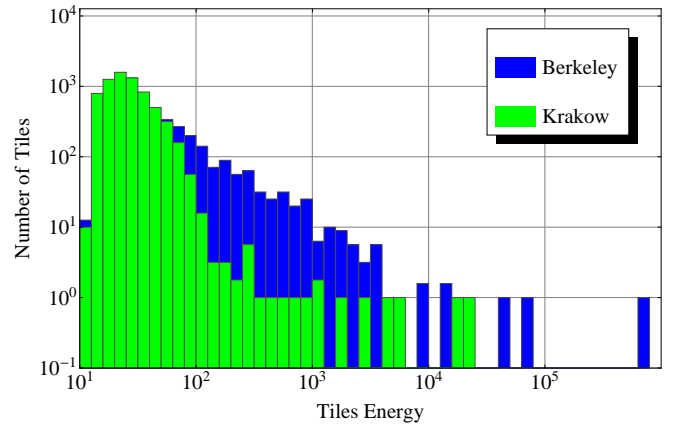


FIG. 6: Histogram showing the number of tiles with energy within a specific energy range for the magnetometer data depicted in Figs. 4 and 5.

related characteristics. Time shifts can be introduced into the data to check for correlated transient events with particular relative delays.

Examination of the time/frequency map of whitened signal energy shown in Fig. 5 reveals that the Kraków instrument produces fewer “loud” transients (associated with high tile energies) than the Berkeley instrument, indicating that the Kraków data more closely follows the signal expected from Gaussian-distributed noise. The loud transients in both instruments are likely due to electromagnetic environmental couplings or technical noise in the instruments themselves (laser light power and frequency noise, etc.). Further investigation is needed to identify the causes of the loud transients and find appropriate methods to eliminate as many sources of loud transients as possible.

Figure 6 is a histogram of the tile energies from the trigger maps in Fig. 5 with the Berkeley magnetometer signal in blue and the Kraków magnetometer signal in green. One observes a roughly one order-of-magnitude excess of events in the Berkeley magnetometer signal compared to the Kraków signal for tile energies above ~ 100 . This indicates problems in the relative quality of the Berkeley data compared to the Kraków data, perhaps a result of environmental noise or technical noise (such as the electronic pick-up noise identified in auxiliary measurements). Such histogram analysis is another useful way to characterize the performance of individual magnetometers in the GNOME.

VI. PROSPECTS

Comagnetometry, where the magnetic field is simultaneously measured with multiple atomic species or devices, is a widely used technique in precision measurements searching for anomalous spin-dependent effects. Comagnetometry with different atomic species of

ten takes advantage of the fact that the relative coupling strengths of an exotic field to electrons and nuclei are generally different from the relative coupling strengths of electrons and nuclei to magnetic fields. A particular example of a comagnetometry scheme that will be investigated for possible use as a GNOME sensor is SERF comagnetometer similar to that described in Ref. [58]. In contrast to the devices used in the demonstration experiment described in the present work, an additional noble gas (helium) is introduced into a vapor cell. When the noble gas has non-zero nuclear spin, the alkali and noble gas spins become strongly coupled through spin-exchange collisions [59, 60]. This coupling can be represented as the effective magnetic field \mathbf{B}_{eff} experienced by one spin species due to the average magnetization \mathbf{M} of the other, due to enhancement of the alkali valence electron density at the noble gas nucleus,

$$\mathbf{B}_{\text{eff}} = \lambda \mathbf{M}, \quad (8)$$

where λ is a parameter determined by the particular properties of the alkali-noble gas spin-exchange [61]. The applied field \mathbf{B} is tuned so that it approximately cancels \mathbf{B}_{eff} experienced by the alkali atoms. The alkali atoms are then in an effective zero-field environment, and because the noble gas magnetization \mathbf{M} adiabatically follows \mathbf{B} , transverse components of \mathbf{B} are automatically compensated by \mathbf{B}_{eff} to first order. Such cancellation only occurs for interactions that couple to spins in proportion to their magnetic moments, leaving the SERF comagnetometer sensitive to anomalous spin couplings to electrons and nuclei [59].

The energy resolution of the latest generation of the SERF comagnetometer, employing Rb as the alkali atom and ^{21}Ne as the noble gas, is $\sim 10^{-23} \text{ eV}/\sqrt{\text{Hz}}$ [58]. This new scheme uses hybrid optical pumping of Rb via spin-exchange collisions with low-density, optically pumped K and off-resonant direct optical probing of Rb spins. This approach allows full optimization of both optical pumping and probing. Because of the relatively small gyromagnetic ratio of ^{21}Ne , the Rb-K- ^{21}Ne SERF comagnetometer has an order of magnitude better energy resolution for the same level of magnetic-field sensitivity as compared to earlier SERF comagnetometers, and may offer advantages in bandwidth. In the future, we plan to develop and optimize the SERF-based comagnetometer for measurements of exotic transient effects.

Independently from the development of SERF-based comagnetometer, the other magnetometer types will be developed as potential GNOME sensors. In particular, we envision using sensors that monitor evolution of various types of spins (proton, neutron, electron). This would add another dimension to our investigations by studying influence of exotic coupling to various fundamental particles.

Another important work envisioned for a future experiment is correlation of the magnetometer readouts with environmental parameters (e.g., magnetic field outside the shield, temperature, etc.). This is motivated by the

fact that despite magnetic shielding, there will inevitably be some level of transient signals and noise associated with the local environment (and possibly with global effects like the solar wind, changes to the Earth's magnetic field, etc.). The environmental-condition data will allow for exclusion/vetoing of data with known systematic issues.

Further step in reducing the influence of magnetic fields on the operation of GNOME is application of Superconducting Quantum Interference Device (SQUID) [62] magnetometers as sensors operating in addition to OMAGs inside the magnetic shields. While the SQUID magnetometers are characterized with magnetometric sensitivity comparable to that of OMAGs, they are not sensitive to exotic spin coupling. Thus, they can be used for vetoing false-positive transient signals.

Ultimately, the GNOME will consist of at least five OMAGs. Four devices will be used for the detection of a DW and of its geometrical properties. Any additional magnetometer would increase the sensitivity of the network. An independent OMAG will serve as cross-check to verify if, based on predicated DW event, a transient signal arises in the magnetometer in a narrow temporal window.

VII. CONCLUSIONS

In this paper, we presented a new experimental scheme enabling investigations of transient exotic spin couplings. It is based on synchronous operation of globally separated optical magnetometers enclosed inside magnetic shields. Correlation of magnetometers' readouts enables filtering local signals induced by environmental and/or technical noise. Moreover, application of vetoing techniques, e.g., via correlation of optical-magnetometer readouts with signals detected with non-optical magnetic-field sensors, enables suppression of influence of global disturbances of magnetic origins, such as solar wind, fluctuation of the Earth's magnetic field, on the operation of the magnetometers. In such an arrangement, the network becomes primarily sensitive to spin coupling of non-magnetic origins, thus it may be used for searches of physics beyond the Standard Model. A specific example of such searches was discussed here by considering coupling of atomic spins to domain walls of axion-like fields. It was demonstrated that with modern state-of-the-art optical magnetometers probing a significant region of currently unconstrained space of parameters of the fields is feasible. The preliminary results obtained based on synchronous operation of two magnetometers located in Kraków and Berkeley were presented and future plans for the network development were outlined.

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- [63] The phases may either be separated in time or may occur simultaneously.
- [64] Although for a minimum uncertainty state, the sensitivity δB_{at} scales as $1/\sqrt{N_{at}}$, for a quantum system with entanglement the scaling could be stronger ($\delta B_{at} \propto 1/N_{at}$). In principle, it should allow for a large improvement in magnetic-field sensitivity of OMAGs. Unfortunately, the entangled states are fragile and rarely improvement of the sensitivity δB_{at} below Eq. (1) is observed [24, 25].
- [65] Note that the sensitivity of the magnetometer is at a level of 10^{-15} T/ $\sqrt{\text{Hz}}$ or better, while the Earth magnetic field is $\approx 4 \times 10^{-5}$ T. Hence even with a shielding factor of $> 10^6$ for DC fields, the magnetometer is still strongly sensitive to the fluctuation of the external fields.
- [66] In order to limit magnetic-field noise due to Johnson currents in the shield, modern magnetic shields have the innermost layer made of ferrite. Although such material has significantly lower magnetic susceptibility than permaloys, in particular, μ -metal, they have orders of magnitude larger resistivity, which suppresses thermal currents in the magnetic-shield layer placed closest to a vapor cell (see Ref. [2] and references therein).
- [67] Formation of the wall from QCD-axion field would lead to disastrous cosmological consequences due to the excessive energy stored in the walls.
- [68] Note that in general, the higher-order couplings to the spins may be considered (see Ref [12] for further details).
- [69] Note that the demonstrated sensitivity of the magnetometer δB is lower.
- [70] The demonstrated sensitivity of the device δB is roughly $10 \text{ fT}/\sqrt{\text{Hz}}$.
- [71] While magnetic shields do not screen exotic interactions, their role in searches for transient exotic couplings require more thorough investigations in the future.